

ESTCP Cost and Performance Report

(WP-200520)



Biological Treatment of Solvent-Based Paint

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ESTCP

ENVIRONMENTAL SECURITY
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ACRONYMS AND ABBREVIATIONS

| | |
|------------------|--|
| BAA | Broad Agency Announcements |
| BBP | butyl benzyl phthalate |
| BOD | biological oxygen demand |
| CFM | cubic feet per minute |
| CFR | Code of Federal Regulations |
| CHRIMP | Consolidated Hazardous Material Reutilization and Inventory Management Program |
| CO ₂ | carbon dioxide |
| COMNAV | Commander of Navy |
| DEM/VAL | demonstrate and validate |
| DoD | Department of Defense |
| DOH | Department of Health |
| DRMO | Defense Reutilization and Marketing Office |
| EPA | Environmental Protection Agency |
| ESL | expired shelf-life |
| ESTCP | Environmental Security Technology Certification Program |
| FK-WTP | Fort Kamehameha Wastewater Treatment Plant |
| FTIR | Fourier Transform Infrared |
| GAC | granular activated carbon |
| H ₂ O | water |
| HP | horsepower |
| IWG | inches of water gauge |
| IWTC | Industrial Wastewater Treatment Complex |
| JGDM | Joint Group on Depot Maintenance |
| MBAS | methylene blue activated substances |
| MIB | moisture integrator bubbler |
| MILSPEC | military specifications |
| MS | moisture separator |
| N/A | not applicable |
| NAVFAC | Naval Facilities Engineering Command |
| NAVFAC ESC | NAVFAC Engineering Service Center |
| NAVFAC HI | NAVFAC Hawaii |
| ND | non-detect |
| NEMA | National Electrical Manufacturer's Association |
| nm | nanometer(s) |

ACRONYMS AND ABBREVIATIONS (continued)

| | |
|-------|--|
| NPDES | National Pollutant Discharge Elimination System |
| NT | not tested |
| O&M | operations and maintenance |
| OSHA | Occupational Safety and Health Administration |
| PVC | polyvinyl chloride |
| RCRA | Resource Conservation and Recovery Act |
| SBAR | Santa Barbara Applied Research, Inc. |
| SBR | sequencing batch reactor |
| SP | standard pressure |
| STLC | soluble threshold limit concentration |
| SVOC | semi-volatile organic compound |
| TCLP | toxicity characteristic leaching procedure |
| TOC | total organic carbon |
| TPH | total petroleum hydrocarbons |
| TSS | total suspended solids |
| TTLC | total threshold limit concentrations |
| TTO | total toxic organic |
| UV | ultraviolet |
| VOC | volatile organic compound |
| WRI | Wastewater Resources Incorporated |
| WWTU | wastewater treatment unit |
| YO817 | Pollution Abatement Technology Demonstration Program |

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1.0 EXECUTIVE SUMMARY

The Naval Facilities Engineering Command (NAVFAC) Engineering Service Center (NAVFAC ESC), under the sponsorship of NAVFAC and the Environmental Security Technology Certification Program (ESTCP), attempted to demonstrate and validate a full-scale treatment system for biodegrading hazardous expired shelf-life (ESL), solvent-based paint into nonhazardous byproducts. Previous research and studies suggested the application was an economically viable process that would reduce the Navy's highest per pound recurring cost.

Two parallel sequencing batch reactors, totaling a working volume of 8600 gal, and associated parts (can crusher, mixing tank, and air biofiltration system) were procured, installed, and tested over a 1-yr period in cooperation with the Industrial Wastewater Treatment Complex (IWTC) in Pearl Harbor, Hawaii. Regulations required for successful treatment were at the federal, state, and local level and included discharge requirements established by the Fort Kamehameha Wastewater Treatment Plant (FK-WTP) for the water; toxicity characteristic leaching procedure (TCLP) requirements for the sludge; and Title V requirements for the air.

Six individual runs were performed on three different types of paint, each run lasting approximately 10 days. Runs 1 and 6 were excluded from the results and analysis. Run 1 was an acclimation period, and for run 6, an atypical, new paint type was delivered that proved much more difficult to treat. For the liquid phase discharge, all requirements were met in runs 2 through 5, except for a few spikes that were addressed by further settling.

All solid phase requirements were met, and Title V requirements in the biofilter exhaust were met 83% of the time. However, despite the successful results for discharge requirements, more questions and issues were raised, and the costs to run the system were exorbitant. Issues of greatest concern are the large quantity of organic matter found in the sludge, indicating incomplete degradation; the cost prohibitive use of granular activated carbon for air polishing; the inability to adequately shear and emulsify the paint; the possible requirement of a Part B permit; and the need for highly trained personnel to operate the system. Finally, the biggest concern was the total cost of treatment. To run the system efficiently, calculations show the system requires \$19.63 per gal of paint whereas hazardous disposal currently only costs \$9.19 per gal of waste. System payback is impossible and annual cost reductions are nonexistent.

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2.0 INTRODUCTION

2.1 BACKGROUND

Paints utilized for military equipment, structures, ships, submarines, and weapons are formulated to stringent military specifications (MILSPEC). After the shelf life has expired, the paint can no longer be used for its original purpose or application. Furthermore, Navy policy prohibits the use of reformulated MILSPEC paint on anything classified as mission-critical; therefore, treatment and off-site disposal are the only two alternatives available for managing this waste. As a result, management and disposal of ESL paint is the Navy's most expensive waste [1]. The problem is particularly acute on ships due to replenishment uncertainty; therefore, overstocked paint occurs when deployed, leading to the offloading of large quantities of ESL paint at their home port. This is an issue that is not limited to the Navy. The Joint Group on Depot Maintenance (JGDM) has also identified disposal of waste paint as a high priority at Department of Defense (DoD) facilities and initiated a project to determine how much paint is collected and the associated disposal costs [2].

The implementation of the Consolidated Hazardous Material Reutilization and Inventory Management Program (CHRIMP) in the early 1990s reduced the inventory of ESL solvent-based paint through recycling and non-mission-critical reuse policies. However, due to the sheer quantities of ESL paint, activities continue to find themselves managing and ultimately disposing of ESL paint at a cost of \$1.70 to \$2.24 per pound, equaling a recurring cost to the Navy in excess of \$6 million per year (1999 dollars) [1].

To address this problem, the NAVFAC tasked the NAVFAC ESC to investigate alternative management methods for ESL solvent-based paint that would concurrently reduce costs and liability associated with the current practice of off-site disposal. The Navy Environmental Sustainability Development to Integration Program (originally the Pollution Abatement Technology Demonstration Program [YO817]) funded the initial effort, which concluded that biological treatment was the most promising technology for treating ESL paint at considerable cost savings and reduction of liability. Other technologies evaluated were steam reforming, incineration, ultrafiltration, activated carbon, and photochemical oxidation. Because the paint is not suspended in water, its high viscosity and solids content preclude the use of ultrafiltration, activated carbon, and photochemical oxidation as primary treatment. However, these technologies are considered viable for processing by-products generated from biologically treating solvent-based paint (e.g., wastewater, slurries).

Given the fuel value of ESL paint, incineration would be a strong candidate, if not the preferred candidate. However, in many states it is virtually impossible to obtain a permit to operate a hazardous waste incinerator. Capital investment for steam reforming proved to be far too expensive; therefore, no further consideration was given to this technology. The demonstration of the biodegradability of resins, activators, and solvents found in bulk ESL solvent-based paint, coupled with the high cost of off-site disposal, created the need for a full-scale demonstration effort.

For the demonstration effort, two 4627-gal biological treatment plants were installed at the IWTC in Pearl Harbor, HI. The completely enclosed systems consist of can crushers, mixing

tanks, treatment tanks, and one air biofiltration system capable of handling the exhaust from both systems. For each experimental run, paint was added along with nutrients and allowed to process for approximately 10 days, with monitoring and sampling being conducted periodically.

2.2 OBJECTIVE OF THE DEMONSTRATION

The overall project objective is to demonstrate and validate (DEM/VAL) the economic feasibility of biological treatment of ESL paint. Specific objectives derived from the pilot scale are:

- Construct and install a full-scale treatment system using commercially available components.
- Optimize operation of the system to treat ESL paint.
- Demonstrate that the degradation end products meet requirements for discharge and disposal.
- Facilitate technology transfer by acquiring design, cost, and performance data.

The long-term objective is to implement the use of biological reactors DoD-wide to reduce the cost and liability associated with the disposal of solvent-based paint.

2.3 REGULATORY DRIVERS

In addition to addressing the number one hazardous waste disposal problem within the Navy, the project addresses the following high-priority Navy Environmental Quality requirements:

- 3.I.11.b Excess Hazardous Material Minimization
- 2.III.01.b Advanced Control and Destruction for Hazardous Wastes

3.0 DEMONSTRATION TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

3.1.1 Biological Wastewater Treatment

Biological treatment of organic rich wastewater is an attractive and very commonly used technology for the removal of dissolved organics and suspended organic solids. The process typically removes more than 90% of suspended organic solids and is the most cost effective treatment available for dissolved organics. Because of its simplicity and versatility, the use of biological treatment has been expanded to treat a wide variety of biodegradable waste and has often become the method of choice for the remediation of contaminated soil and water. The basic requirement for the process is mixing a near neutral pH and, for most applications, an aeration system, which provides oxygen and additional mixing.

Biological treatment systems are typically designed to promote the growth of the naturally occurring bacteria adapted for the targeted waste. Nitrogen, phosphorus, and small amounts of vitamins and amino acids are added to promote bacterial growth. The process requires a residence time adequate for the bacteria to fully degrade the organics present. In the case of industrial wastewater treatment, excessive concentrations of heavy metals, some organic compounds (such as chlorinated solvents), high salinity, or extreme pH or temperature can hinder and, in some cases, even poison biological treatment systems. But these effects are usually transient and systems rapidly recover when normal conditions are restored.

The end product of biological treatment is carbon dioxide (CO₂), water (H₂O), and biomass. Biomass is inorganic solids, dead bacteria, cell remnants, and other insoluble organic residue. The volume produced depends upon the capacity of the system and the proportion of the food source that is converted to biomass versus the proportion used for energy. Because dead bacteria can be broken down and used as a source of nutrients by the active biomass, recycling solids back through the reactor can reduce the amount of biomass for disposal and promote more rapid degradation in the reactor. However, buildup will eventually force the periodic harvest and disposal of accumulated solids.

Leftover products from a biological treatment process include metals, insoluble organic matter, and other inorganic contents of the original media. Unless the concentration of metals exceeds allowable limits, this residue is usually nontoxic and nonhazardous and can be landfarmed, composted, or captured in a filter press and landfilled.

Most industrial biological treatment systems will also require air biofiltration. Industrial waste streams can often contain volatile organic compounds (VOC) and semi-volatile organic compounds (SVOC), and/or these compounds might be formed as intermediaries during the treatment process. Vigorous aeration and mixing enhance the release of these often-regulated compounds, resulting in emissions. To capture and degrade VOCs and SVOCs, air (vented from reactors) is passed through a biofilter packed with a coarse media that provides support for the growth of bacteria. Typically, to ensure that the release of air meets all regulations, an activated carbon filter is added to the end of the air filtration process for polishing. An overall view of the process is shown in Appendix B.

Figure 1 is a complete flow diagram for the entire ESL paint degradation system.

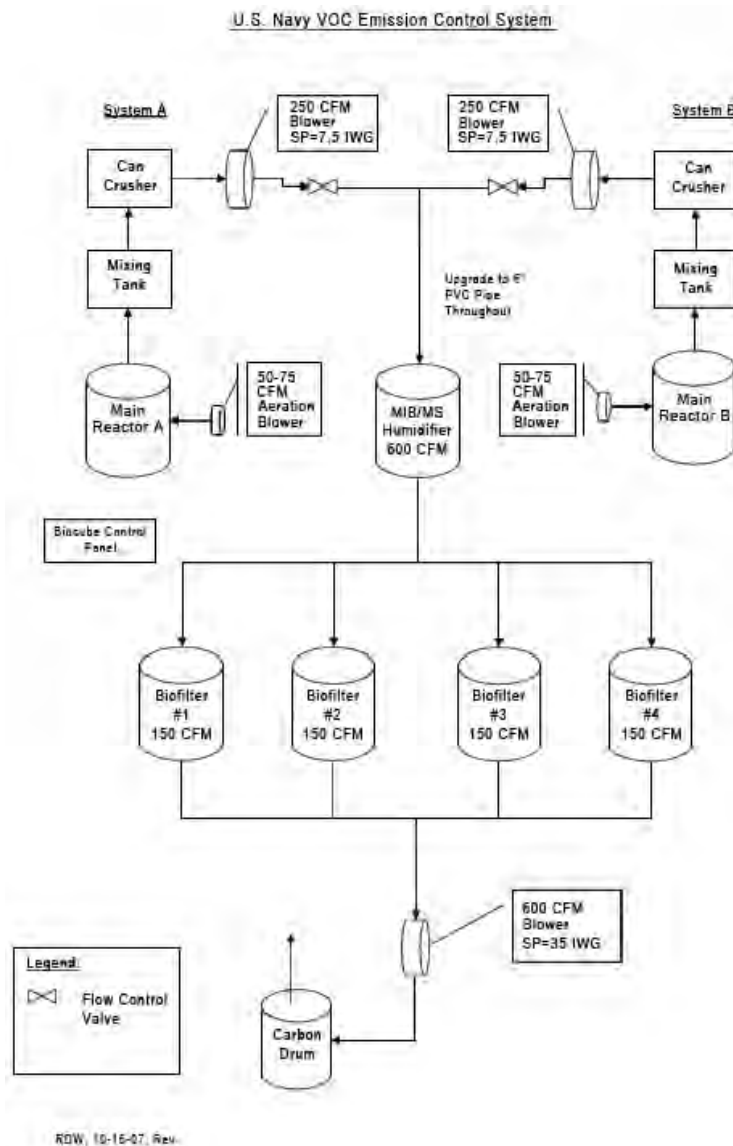


Figure 1. Flow diagram of complete ESL paint degradation system.

SP = standard pressure; CFM = cubic feet per minute; IWG = inches of water gauge;
MIB = moisture integrator bubbler; MS = moisture separator

The project did not propose to treat specialty paints with heavy metals (such as anti-fouling paints), latex, or oil paints. Oil and latex paints were not included because they are not used aboard ships and have greater recycling potential. Specialty paints containing heavy metals were not included either but could be treated if provisions (e.g., precipitation, ion exchange, electrocoagulation) were made to capture the heavy metals following biodegradation of the solvents, resins, and activators.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

3.2.1 Alternative Technologies

Based upon the composition of the individual paints most commonly used, potentially applicable treatment technologies were identified and evaluated, such as biodegradation, carbon adsorption, incineration, photochemical oxidation, steam reforming, and ultrafiltration. Detailed information regarding all of these processes can be found in TM-XXXX-ENV (2005) [3].

Carbon adsorption is highly effective; however, removing high concentrations of contaminants can be problematic and very expensive, and recovered contaminants from the regeneration process can require additional handling.

Incineration is effective in reducing the volume of waste, and if metals are within allowable limits, the ash can be typically landfilled. However, if the waste contains nitrogen, other by-products can be produced in the incineration process that would require removal with additional equipment. Furthermore, permitting and operating a small on-site incinerator in most areas is very difficult and in California is prohibited.

Photochemical oxidation uses ultraviolet (UV) light and oxidants to oxidize organic material in a waste stream. Because of the makeup of a paint waste stream, the energy required for the lamps and the required light change frequency, the process would be cost-prohibitive for treating paint.

For ultrafiltration of a paint waste stream, the paint would have to be delivered to the membranes fully dissolved or suspended. Furthermore, because ultrafiltration does not necessarily remove or destroy hazardous components, additional treatment technologies would have to be applied.

Of the remaining technologies, only biological treatment and the physical chemical process known as steam reforming are appropriate for treating waste paint. Steam reforming uses heat to vaporize liquid or solid organic waste. The volatilized compounds are then mixed with superheated steam and passed through a fluidized bed, converting them to carbon monoxide and hydrogen. It is a starting point for the synthesis of methanol. Consulting with a steam-reforming company, it was determined that ESL paint could be treated. However, further tests regarding the fate of nonvolatile resins and toxicity of the residue would be required.

To reduce the amount of residual biomass, highly organic waste streams can also be treated in an anaerobic digester, which has the added benefit of producing methane that can then be captured and used as fuel. However, anaerobic processes tend to be slower than aerobic processes, and the longer treatment times may require larger capacity systems than comparable aerobic systems.

Based upon the bench-scale studies conducted by NAVFAC ESC, it was determined that two-part paint, and more specifically, the activators and resins, can be biologically degraded. Therefore, an economic analysis was conducted to compare biological treatment to steam reforming. Biological treatment was calculated as the better choice with a lower initial cost and a payback of less than 1 year. See the Final Report for more details of the analysis and costs.

3.2.2 Biological Treatment

Sequencing batch reactors for biological treatment is a mature technology, as described in Section 2.1, and is increasingly used to treat a variety of high biological oxygen demand (BOD) waste streams [4, 5, 6, 7, 8, 9, 10, 11].

The main theoretical advantages of utilizing this technology for the treatment of paint are:

- Degrading nonvolatile resins, activators, and solvents
- Degrading VOCs
- Reducing paint management and handling required by land filling
- Operating a simple and relatively compact process.

The main limitations of the technology for the DEM/VAL are:

- Inadequate emulsification results in poor to no degradation.
- Excessive ESL paint loading impedes performance and poisons the system.
- Pilot study did not establish a viable paint-to-water ratio.
- High concentrations of heavy metals may poison the system.
- Pilot study did not analyze total toxic organic (TTO) requirements.
- Pilot study did not provide adequate data to demonstrate cost effectiveness.

Operational issues include:

- Handling and disposal of accumulated reactor sludge
- Handling and disposal of biomass with excessive metals or other regulated compounds
- Emulsifying paint adequately for digestion
- Minimizing foam production during operation.

3.2.3 Pilot Study Economic Analysis

The full details of the economic analysis performed after the completion of the pilot study can be found in “Biodegradation of Expired Shelf Life Solvent Based Paint: Results of a Pilot Study That Used a Sequencing Batch Reactor and Biofilter to Degrade Paint Resins, Activators, and Solvents” (2005). In summary, cost predictions were made based on the following conditions: treatment of 2000 – 4000 gal of paint per month; cost incurrences based on the design, purchase, installation, and operation of a 10,000-gal sequencing batch reactor in Pearl Harbor; and current costs of paint disposal based on numbers provided (470,000 lb of ESL paint at \$1.98 per lb). Based on the annual cost of \$930,600 per year to dispose of the paint, the author of the pilot study predicted a payback of less than 1 year.

4.0 PERFORMANCE OBJECTIVES

Table 1 presents a summary of quantitative and qualitative performance objectives in the biological treatment of ESL paint.

Table 1. Quantitative and qualitative performance objectives.

| Performance Objective | Data Requirements | Success Criteria | Results |
|--|---|--|--|
| Quantitative Performance Objectives | | | |
| Aerobic digestion of ESL paint | Establish a residence time in the reactor that balances cost and digestion requirements. | Demonstrate a residence time between 8 - 10 days. | A residence time of 4 days is required to reduce the overall treatment cost. |
| | Meet a predetermined level of paint degradation in reactor. | >95% | 95% degradation in 0% test runs. |
| Post digestion-liquid phase | Discharge finished liquid to sewer by meeting Environmental Protection Agency (EPA), Department of Health (DOH), and Commander of Navy (COMNAV) requirements. | Meet TTO, metals, and other miscellaneous requirements—See Table 4-2 in the Final Report for constituent list. | <ul style="list-style-type: none"> • TTO requirements were met in 0% of the discharge samples. • TSS requirements were met in 100% of the discharge samples. • Heavy metal requirements were met in 100% of the discharge samples. • Miscellaneous metal requirements were met in 100% of the discharge samples. |
| Post digestion-solid phase | Dispose of finished sludge. | Meet TCLP requirements as nonhazardous for metals and organics. See Final Report for constituent list. | <ul style="list-style-type: none"> • TCLP metal requirements were met in 100% of samples. • TCLP organics requirements were met in 100% of samples. |
| Post digestion-air phase | Establish biofilters to efficiently remove VOC compounds and meet exhaust Title V requirements. | 95% or greater VOC removal. | <ul style="list-style-type: none"> • Biofilters were 22 to 93% efficient. • GAC* filter met Title V requirements in 83% of instantaneous samples. However, total VOC removal met Title V requirements in 100% of test runs. |
| Cost reductions | Show system payback. | Payback in < 2 years. | Payback is questionable in the current design and operational performance. More testing is required. |
| | Show annual cost reductions as compared to contract disposal. | < \$9.19 per gallon | Operation and maintenance cost of \$19.63 per gal of paint under DEM/VAL operation with 60 gal throughput. |

*GAC = granular activated carbon

Table 1. Quantitative and qualitative performance objectives (continued).

| Performance Objective | Data Requirements | Success Criteria | Results |
|---|---|---|---|
| Qualitative Performance Objectives | | | |
| System parts | Component procurement | Use readily available off-the-shelf components. | System was constructed from available off-the-shelf components. |
| System assembly | Meet estimated time-line. | Reactors, pumps, valves, can-crusher, and biofilter procured and installed in 3 months. | Due to government mechanism (Broad Agency Announcement [BAA]) to hire contractor, significant deficiencies were revealed after initial installation was completed. Timeline extended 3 years to correct deficiencies. |
| Start-up and optimization | Meet estimated time-lines. | Start-up within 1 month of installation. | After installation issues were resolved, the system was successfully started up within 1 month. |
| | | Optimization within two runs. | Optimization was not reached during the DEM/VAL. |
| Ease of operation | Incorporate automation. | Minimize operator time and requirements. | Manpower was reduced to the maximum extent possible. |
| Operator safety | Operate system without creating safety hazards. | Meet all fire, Occupational Safety and Health Administration (OSHA), etc. requirements. | All requirements were met. |
| Operational requirements | Perform routine operational tasks. | No system failure due to operational task neglect. | The system was not hindered by operational neglect during the entire DEM/VAL. |
| Maintenance requirements | Perform routine maintenance and calibration. | No system failure due to maintenance neglect. | The system was not hindered by maintenance neglect during the entire DEM/VAL. |
| Reliability | Operate system as designed. | No equipment failures. | No component failure except for two centrifugal pumps due to incompatibility with the constituents of the waste stream. This was an additional contractor issue. |

5.0 SITE/PLATFORM DESCRIPTION

5.1 TEST PLATFORM FACILITIES

IWTC at Pearl Harbor was selected as the prime test platform. IWTC supports the ESL paint for all ship classes serviced by Pearl Harbor Shipyards.

5.2 PRESENT IWTC OPERATIONS

The IWTC currently stores and treats waste generated by federal government facilities in the State of Hawaii. The hazardous waste storage permit allows the facility to store up to 27,280 gal of segregated waste in designated storage bays prior to either treatment or off-site disposal.

Treated wastewater is discharged to the Navy-operated FK-WTP, a National Pollutant Discharge Elimination System (NPDES)-permitted facility. Sludge generated is disposed of through the Defense Reutilization and Marketing Office (DRMO).

5.3 SITE-RELATED PERMITS AND REGULATIONS

Under the Resource Conservation and Recovery Act (RCRA) of 1976, the EPA classifies ESL solvent-based paints as solid waste. The EPA regulates ESL solvent-based paints based on their makeup of various toxic organic compounds, their ignitability, and the priority metals in the paint. Because many of the paint's individual constituents are termed hazardous, paint is controlled from "cradle-to-grave" as a hazardous waste for not meeting ignitability and toxicity requirements. The categorical codes used to classify paints are D001 (ignitability), D005 (barium), D007 (chromium), and D035 (EPA Toxicity).

Because paint is a federally regulated waste, treating paint for disposal will likely require a Part B permit issued by the EPA or state. Regulation 40 Code of Federal Regulations (CFR) 264.1(g)(6) excludes owners or operators of an elementary neutralization unit or a wastewater treatment unit (WWTU), as defined in §260.10, from a Part B permit. However, a biological treatment system for processing ESL solvent-based paint is not classified as a WWTU and would subsequently require a Part B permit, even though water generated from the process would most likely be discharged to a NPDES-permitted facility.

NAVFAC Hawaii's (NAVFAC HI) Environmental Department acquired permission from the Hawaii EPA's DOH to demonstrate and validate on-site treatment of ESL solvent-based paint. Permission was contingent upon no paint waste being used during the demonstration phase. The DOH also required the use of activated carbon to polish any emissions generated from this process. In addition, water generated or used by the process was tested prior to discharge to ensure compliance with the IWTC pretreatment NPDES permit requirements. All other waste byproducts were also disposed of according to federal, state, and local requirements.

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6.0 TEST DESIGN

6.1 LABORATORY/BENCH-SCALE TESTING

As described in Section 2.2.2, NAVFAC ESC conducted bench scale feasibility testing of solvent-based paint. Full descriptions and results can be found in the TM-2368-ENV (2004) [12]. Results demonstrated that both resins and activators of two-part solvent-based paints could possibly be degraded provided conducive conditions.

A detailed description of the equipment, system operations, and laboratory analyses can be found in the Final Report.

6.2 REAL WORLD TESTING

6.2.1 Pilot-Scale Testing

Described in Section 2.2.3, NAVFAC ESC conducted a pilot study of an aerobic digestion for solvent-based paint in Pearl Harbor, HI. Full details and results of this project are in TMXXXX-ENV (2005) [3].

Five 20-gal stainless steel sequence reactors were installed for the pilot project, as well as airpowered centrifugal pumps, pH controllers, an exhaust blower, compost-filled biofilters, and an activated carbon drum. The residence time for the reactors was set at 10 days and the residence time of air in the biofilters was estimated at 10 minutes. One gal of paint (resin or activator, always separate) and approximately 20 gal of water were used for each test. Nitrogen and phosphorus, required for bacteria proliferation, were supplied by adding ammonium phosphate fertilizer. Yeast extract and peptone were added as sources of vitamins and amino acids.

According to the pilot results, four two-part solvent-based paints were successfully treated and degraded, although the testing on the water phase was limited to Fourier Transform Infrared (FTIR) spectroscopy and the COMNAV regulations. No TTO analysis was completed. Analysis of the solids generated during the pilot study indicated that the solids are not hazardous and the levels of priority metals were below the total threshold limit concentrations (TTLC) for landfilling.

A detailed description of the equipment, system operations, and laboratory analyses can be found in the Final Report.

6.2.2 Full-Scale Demonstration/Validation Design and Installation

Two treatment systems were positioned inside the two free bays within the IWTC. The selection was based on space availability and the minimization of site preparation costs. Subsequently, utilities (i.e., air, electricity, and water) were provided for the two free bays to accommodate system requirements. Electrical service (100 amps) was provided to run both systems, including the biofilters. A 2-inch freshwater line and a 1-inch air line were also provided for each bay. All tanks, pumps, and can crushers were placed inside the bays for secondary containment. The

system motor control panels, pH adjustment subsystems, and the nutrient-addition subsystems were placed outside the bays.

Outside the IWTC complex, a pad was poured for accommodating the biofilter system. The biofilter system, including the motor control panel, was placed on top of the pad. A humidifier water transfer system was placed adjacent to the biofilter system motor control panel.

Exhaust ports for all tanks and can crushers were plumbed together and, subsequently, plumbed into the biofilter system. This ensured that all air streams generated during the treatment process were treated prior to discharge to the atmosphere. Sampling ports were provided at the inlet (discharge side) of the biofilters and at the discharge side of the activated carbon tank.

Stainless steel tanks and piping were used for all equipment that came in direct contact with the system liquor. Schedule 80 polyvinyl chloride (PVC) piping was used for all airways. Flow meters and manual valves were installed at the discharge side of the blowers on the can crushers for air control.

All electrical components and motors placed inside the bays required a National Electrical Manufacturer's Association (NEMA) 7 rating. In addition, installation of all conduit and conductors were installed in conformance with NEMA 7 requirements. All other electrical installations, including subsystems and system motor control panel installed outside the bays, did not require NEMA 7 rating.

A detailed description of the equipment, system operations, and laboratory analyses can be found in the Final Report.

7.0 PERFORMANCE ASSESSMENT

7.1 LABORATORY/BENCH SCALE

Samples were taken from test flasks at regular intervals, and the optical density at 520 nanometers (nm) was measured as an indicator of bacterial growth. If the bacteria are using the organic components in the paint as a food and energy source, then the optical density, which is proportional to the number of bacteria, will increase until some limit is reached. Samples were also extracted with hexane, filtered with 0.2- μm nylon filter and analyzed using gas chromatography and FTIR. These analyses will show peak disappearance with degradation.

Bacterial growth on base and activator supplemented medium is shown in Figure 2. While both components supported significant growth, growth is slower on the activator. The explanation reported was that one or more of the compounds were toxic or the bacteria were not well enough adapted to these compounds. However, the spectra (Figures 3 through 5) demonstrated changes consistent with biodegradation, and conclusions were drawn from this that degradation occurred. Comparing Figures 3 and 5 shows that adsorption bands characteristic of the activator (e.g., the broad band at $2000 - 2500\text{ cm}^{-1}$ found only in the activator) are completely absent after 2 weeks of bacterial growth. Peaks in the spectrum of the base (Figure 4) show absorption bands at 3500 cm^{-1} (C-O), 2700 cm^{-1} (C-H), and 1700 cm^{-1} (C=O and C=C) characteristic of the polyester backbone (Figure 5). The spectrum of the degraded resin (Figure 5) lacks all of these peaks.

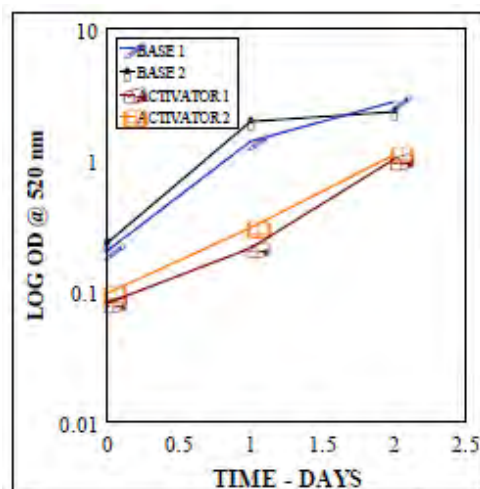


Figure 2. Growth of duplicate cultures derived from oily sludge degrading microbial consortia on polyurethane base and activator.

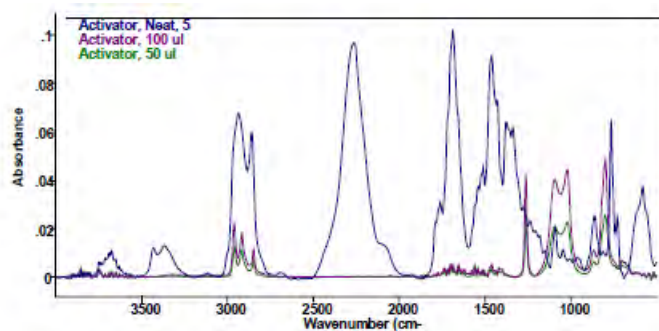


Figure 3. FTIR spectrum of polyurethane activator and hexane extracts of 2-week cultures.

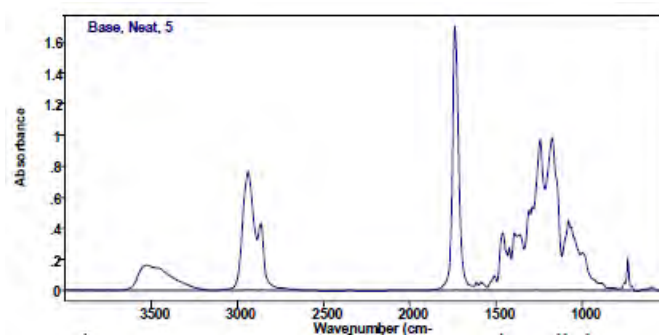


Figure 4. FTIR spectrum of polyurethane resin applied to a potassium bromide window and dried in a desiccator prior to running the spectrum.

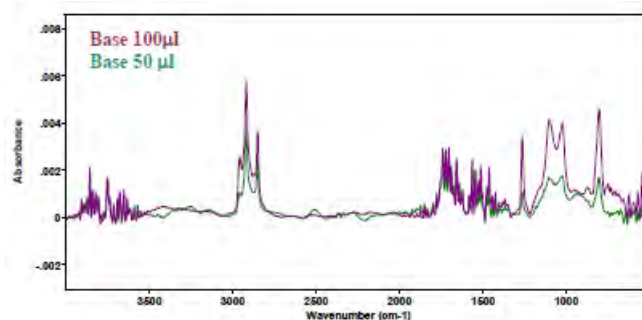


Figure 5. FTIR spectrum of hexane extracts of base fed cultures after 2 weeks of growth.

7.2 PILOT-SCALE

As described in Section 2.2.3, NAVFAC ESC conducted a pilot study of aerobic digestion for solvent-based paint in Pearl Harbor, HI. Full details and results of this project are in TMXXXX-ENV (2005) [3].

Testing on the water phase for the pilot study was limited to FTIR analysis and the COMNAV regulations. No TTO analysis was completed. Testing on the air phase was limited to FTIR analysis on a small number of VOC compounds. Summarized results of the pilot study are shown in Table 2 and Figures 6 and 7. Figure 6 shows degradation results in the reactors and Table 2 and Figure 7 detail degradation of compounds through the biofilters.

Table 2. Specific organic compounds tested in air and their respective percent removal.

| Peak # | Compound | Percent Removal |
|--------|--------------------------|-----------------|
| 1 | Methyl amyl ketone | >95 |
| 2 | Tetrahydrofuran | 70 |
| 3 | Methyl isoamyl ketone | >95 |
| 4 | 4-methyl-2-pentanone | 70 |
| 5 | 1-methylethyl benzene | >95 |
| 6 | Propylbenzene | >95 |
| 7 | 1-ethyl-3-methyl benzene | >95 |
| 8 | 1,3,5-triethyl benzene | >95 |
| 9 | 1-ethyl-2-methylbenzene | >95 |
| 10 | 1,2,4-trimethyl benzene | >95 |
| 11 | 1,2,3-triethyl benzene | >95 |
| IS | Internal standard | N/A |

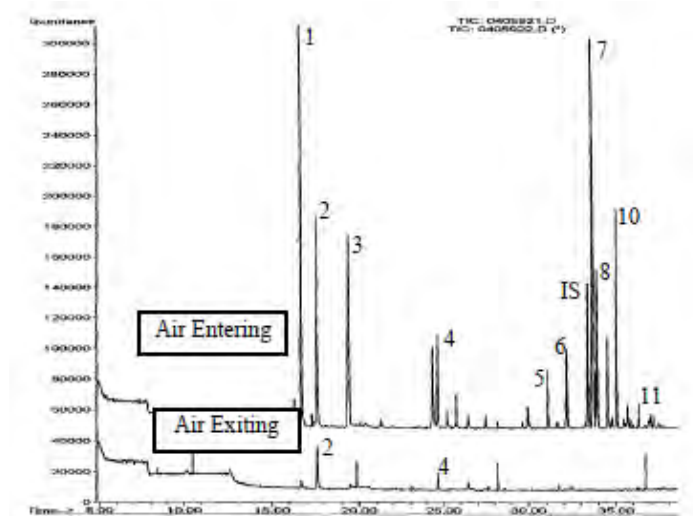


Figure 6. FTIR graph of water tested from the pilot-scale reactor.

Gas chromatogram of air entering and exiting the biofilters.

The identity of the numbered peaks is shown in Table 2.

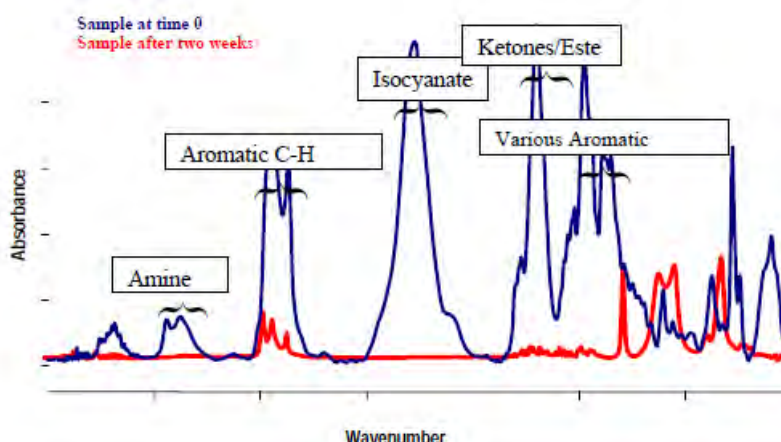


Figure 7. Gas chromatogram graphically depicting degradation of VOCs through the biofilters.

FTIR spectra of fresh polyurethane resin (time 0) and after 2 weeks of degradation. Absorption bands characteristic of the resin are annotated on the spectra.

Through an FTIR analysis of the polyester resin, Figure 6 depicts graphically the disappearance of the aromatic C-H bond after 2 weeks, possibly indicating that the aromatic ring was degraded. In the air, reductions of greater than 95% in most of the VOCs tested through the biofilters were seen. Table 2 lists the specific compounds tested and their respective degradation percentages and Figure 7 shows these results graphically.

To determine if the water phase from the treatment process met the COMNAV Pearl Harbor Base Limits for discharges of treated water from the IWTC to the sanitary sewer, approximately 500 gal of wastewater from the reactors was accumulated on site and analyzed for constituents specified in the COMNAV base limits. These results are shown in Table 3 along with the COMNAV base regulations. The results show that the wastewater discharged from the reactors, following biological treatment of ESL paint, meets requirements for discharge to the NPDES-regulated treatment plant. Sulfide is the only regulated constituent that was elevated. It was surmised that because the tank used to accumulate the effluent was not mixed, it became anaerobic, allowing sulfide production. Under normal operations, this would not occur.

Solids accumulated in the reactors were sampled and analyzed for total metals. The report states that the solids had levels of priority metals below the TTLC and soluble threshold limit concentration (STLC) for landfill disposal. The concentrations of most of the metals were also below the practical quantization limit (0.005 – 0.7 mg/L).

**Table 3. COMNAV Pearl Harbor base limits
for discharges and sample results.**

| Parameter | COMNAV Base Limit (mg/L) | Sample Results (mg/L) |
|--|---|--------------------------------------|
| Ag | 0.43 | <0.030 |
| As | 0.50 | <0.130 |
| Ba | 50.00 | 0.01 |
| Be | 0.20 | <0.010 |
| Cd | 0.69 | <0.010 |
| Cr | 2.77 | <0.087 |
| Cr6+ | 0.50 | 0.11 |
| Cu | 3.38 | 1.48 |
| Hg | 0.05 | 0.00 |
| Mn | N/A | N/A |
| Ni | 3.98 | 0.23 |
| Pb | 0.69 | 0.06 |
| Se | 0.90 | <0.12 |
| Sn | 10.00 | <0.050 |
| Ti | 0.50 | <0.080 |
| Zn | 2.61 | 0.22 |
| pH range | 5.5 - 9.5 | 7.20 |
| Total cyanide | 1.20 | N/A |
| Sulfide | 5.00 | 5.00 |
| Total organic carbon (TOC) | 1200.00 | 423.00 |
| Total petroleum hydrocarbons (TPH) | 25.00 | <5.00 |
| Oil and grease | 160.00 | N/A |
| Nitrites | 5.00 | N/A |
| Hydrazine | 5.00 | N/A |
| Peroxide | 5.00 | N/A |
| Chlorine | 50.00 | N/A |
| Total suspended solids (TSS) | 600.00 | 300.00 |
| Methylene blue activated substances (MBAS) | 30.00 | N/A |

7.3 FULL-SCALE DEMONSTRATION/VALIDATION RESULTS

All data for the DEM/VAL can be reviewed in the Final Report. Full-profile analyses were conducted on Runs 2 through 6. Results of the analyses on Runs 2 through 5 are analyzed for this report and used for cost calculations, while Runs 1 and 6 were excluded. Because Run 1 was a startup phase and was used as a time period for acclimating the biomass and establishing paint degrading specific bacteria, the results are not conclusive for the results analysis. A silicone based paint was received and utilized for Run 6. However, the sludge from this test run was never analyzed due to lack of funds. Therefore, it was decided not to include these results as

well. Sample results for these test runs can be reviewed in the appendices. For this section, the results based on Section 3.0's Performance Objectives are listed in order.

7.3.1 Quantitative Performance Objectives

7.3.1.1 Aerobic Digestion of ESL Paint

Under the pilot study, it was deduced that a residence time of 8-10 days would be both physically and economically feasible. However, the DEM/VAL results showed that an optimal environment was never actually reached during the DEM/VAL phase and even if degradation was successful in 8-10 days, based on the amount of paint throughput, the system would not be cost effective. Table 4 summarizes the paint throughput and associated cost comparison based on the following: DEM/VAL VOC biofiltration data, 1.395% liquor, run time of 4 days, and running the system every week of the year. Current disposal cost for hazardous waste through DRMO is \$9.19 per gal of paint. The full economic analysis is detailed in Section 7.0.

Table 4. Cost comparison of paint treatment versus paint disposal based on DEM/VAL biofilter efficiency numbers.

| Value | Condition |
|--------------|--|
| 4300 | Gallon tank |
| 1.395% | Maximum water: paint liquor treatable |
| 60 | Gallons of paint treated per run |
| 4 | Minimum number of days for theoretical residence time |
| 52 | Maximum number of runs per year |
| 3120 | Maximum gallons of paint that can be treated in one year |
| \$61,245.60 | Cost to treat 3120 gal of paint |
| \$19.63 | Cost per gallon for treatment under current conditions |

Another way to address the success of the aerobic digestion of ESL paint is to meet a predetermined level of paint degradation in the reactor. There is no supporting data available from either the bench or pilot scales that shows any sort of quantitative degradation; only a graphical representation of a disappearance of compounds from the water phase. For the exception of the VOCs measured, no conclusive data at the DEM/VAL level is available either. For future research, developing test methods and/or testing schemes for evaluating the degradation of these constituents must be established before continuing with this process.

7.3.1.2 Results from Field Test of Sequencing Batch Reactor (SBR) Prototype at Pearl Harbor

Test samples were analyzed at three stages; the liquid phase (wastewater), solid phase (sludge residue), and air phase (filtration).

7.3.1.3 Post Digestion-Liquid Phase

After 10 days of processing the paint, air and water samples were taken prior to transferring the contents to the dedicated holding tank. In order to discharge to the FK-WTP, the COMNAV base limits (which are more stringent than the EPA requirements) and TTO requirements had to be

met. Table 5 shows the COMNAV base limits and results for each specific constituent and parameter. Even though the water was not clarified, most of the results listed in Table 5 would pass COMNAV requirements with the exception of titanium and zinc for Run 3, copper for Run 5, TPH for Run 5, and TTO and total suspended solids for all of the runs.

Table 5. Results reported for constituent requirements.
(In milligrams per liter)

| Parameter | COMNAV Base Limit (mg/L) | Run 2 Results (mg/L) | Run 3 Results (mg/L) | Run 4 Results (mg/L) | Run 5 Results (mg/L) |
|------------------|--------------------------|----------------------|----------------------|----------------------|----------------------|
| Ag | 0.430 | 0.000 | 0.000 | 0.002 | 0.001 |
| As | 0.500 | 0.008 | 0.011 | 0.012 | 0.011 |
| Ba | 50.000 | 0.100 | 2.700 | 0.284 | 0.976 |
| Be | 0.200 | 0.000 | 0.002 | 0.001 | 0.001 |
| Cd | 0.690 | 0.006 | 0.054 | 0.038 | 0.016 |
| Cr | 2.770 | 0.031 | 0.320 | 0.243 | 0.126 |
| Cr ⁶⁺ | 0.500 | ND | ND | ND | 0.031 |
| Cu | 3.380 | 0.384 | 1.080 | 1.485 | 3.725 [1.25] |
| Hg | 0.050 | 0.000 | 0.000 | ND | ND |
| Mn | N/A | 0.016 | 0.135 | 0.091 | 0.079 |
| Ni | 3.980 | 0.038 | 0.120 | 0.132 | 0.099 |
| Pb | 0.690 | 0.016 | 0.167 | 0.106 | 0.079 |
| Se | 0.900 | 0.002 | 0.004 | ND | ND |
| Sn | 10.000 | 0.000 | 0.049 | 0.073 | 0.048 |
| Ti | 0.500 | 0.088 | 1.690 [ND] | 0.347 | 0.453 |
| Zn | 2.610 | 0.394 | 3.160 [0.145] | 2.100 | 1.965 |
| pH range | 5.5 – 9.5 | 7.860 | 7.220 | 8.310 | 8.990 |
| Total cyanide | 1.200 | NT | NT | NT | NT |
| Sulfide | 5.000 | NT | NT | NT | NT |
| TOC | 1200.000 | 144 | 148.000 | 724.000 | 619.000 |
| TPH | 25.000 | NT | [ND] | [33.7] | [ND] |
| Oil and grease | 150.000 | [ND] | [ND] | [66] | [ND] |
| Nitrites* | 5.000 | 0.02 | 0.031 | 0.039 | 2.84 |
| Hydrazine | 5.000 | [ND] | [ND] | [ND] | [ND] |
| Peroxide | 5.000 | [ND] | [ND] | [2.0] | [ND] |
| Chlorine | 50.000 | [ND] | [ND] | [ND] | [ND] |
| TSS | 600.000 | 616.000 [12] | 3490.000 [34] | 1120.000 [310] | 2510.000 [88] |
| MBAS | 30.000 | [1.500] | [1.0] | [+] | [.8] |
| TTO | 2.13 | 33.3404 | 19.36612 | 8.3565 | 43.1553 |

* Measured as nitrate+nitrite as nitrogen.

[] These constituents were tested for by the activity. The rest were completed by the contracted lab, Columbia Analytical Services.

NT-Not tested.

ND-Non-detect

N/A-Not applicable to this system

+ -MBAS determination could not be made because an emulsion formed during chloroform extraction.

Yellow highlighted entries indicate results out of compliance with COMNAV requirements when first tested, but passed when retested after water settled (as shown in values inside brackets).

Orange highlighted entries indicate clarified water was polished through granular activated carbon (GAC), but final analytical results were never received.

After the water was transferred to the dedicated holding tank and allowed to settle, another set of samples were taken by the activity to ensure that the water passed COMNAV base limits. All COMNAV base limits were met for all test runs with the exception of TTO. Based on this information, the metals were tied to the suspended solids and not necessarily dissolved in the water phase. Although two types of solids were generated, biomass and undegraded paint, it is not clear if the metals in the suspended solids were part of the biomass or small particles consisting of undegraded paint.

The 2.13 mg/L TTO limit was never met (see Table 6-15 in Final Report for more detail). However, if the compound butyl benzyl phthalate (BBP) (an SVOC) were removed from the totals, the results for TTO for all runs, except one, are within compliance, as presented in Table 6.

Table 6. TTO for all four runs minus the semi-volatile compound, BBP.

| Organic Compound | Run 2 Results (mg/L) | Run 3 Results (mg/L) | Run 4 Results (mg/L) | Run 5 Results (mg/L) |
|-------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| TTO | 33.3404 | 19.36612 | 8.3565 | 43.1553 |
| BBP | 33 | 19 | 4.7 | 42 |
| TTO minus BBP | 0.3404 | 0.36612 | 3.6565 | 1.1553 |

BBP is typically a degradable organic compound. More research would be required to assess the degradation issue.

FTIR analysis was utilized for the liquid phase to determine levels of biodegradation and characterize the constituents. Three samples over time (early in the process, mid-process, and at the end) were taken for each run to represent progressive digestion of the paint.

Figures 8, 9, 10, and 11 present the FTIR spectra of the three samples for each run. Figures 8 and 9 graph the results of an acrylic resin, Figure 10 is of a solvent-based enamel, and Figure 11 graphs the spectra for an epoxy-polyamide resin. The reduction in certain peaks depicts successful degradation of properly emulsified paints or solidification of paint components.

The spectra from Run 2 with an acrylic resin (Figure 8), suggests that significant degradation of organic matter or setting and settling of the paint has occurred. Hydrocarbon peaks in the 3000 to 2800 cm^{-1} range significantly decreased over time and the carbonyl peak at 1728 cm^{-1} has nearly disappeared. For Run 3 (Figure 9), the same type of acrylic resin was biodegraded with the same organic removal or setting and settling results as in the previous run. Figure 10 graphs the spectra from Run 4, in which solvent-based enamel was tested for biodegradation. The results are more inconclusive because, even with the first sample of the run, the hydrocarbon peaks are nearly nonexistent. Two conclusions could be drawn: 1) emulsification was inadequate and most of the paint simply settled, or 2) the microbes digested the organic extremely quickly. The biodegradation of an epoxy polyamide resin from Run 5 is depicted in Figure 11. Similarly, as in the Run 3 results, the resin and hydrocarbon peaks are nearly nonexistent, indicating quick degradation or poor emulsification and subsequent settling of the paint. Based on the amount of

sludge that was generated during the DEM/VAL, it can be concluded that the majority of the paint, with the exception of the VOCs, set and settled to the bottom of the reactors.

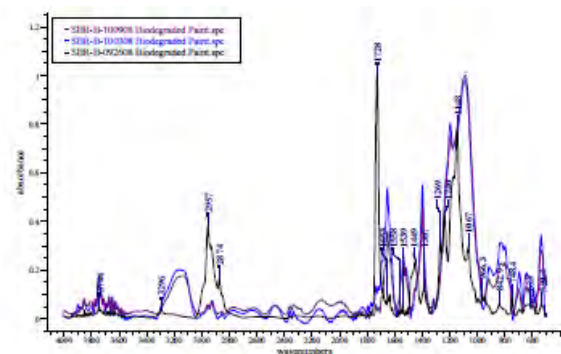


Figure 8. FTIR spectra of biodegraded acrylic resin 1.

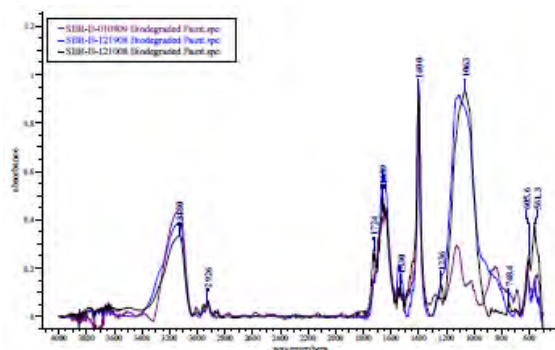


Figure 9. FTIR spectra of biodegraded acrylic resin 2.

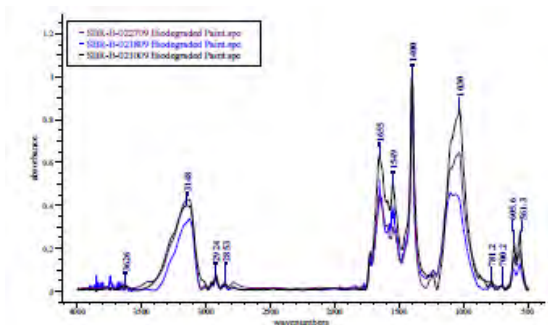


Figure 10. FTIR spectra of biodegraded solvent-based enamel.

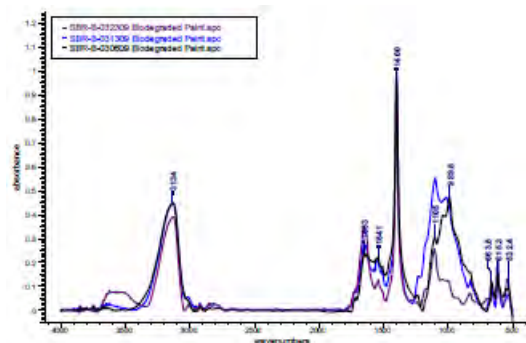


Figure 11. FTIR spectra of biodegraded epoxy polyamide resin.

Prior to clarification, most of the COMNAV requirements were met individually during the DEM/VAL. After clarification, the water phase met all FK-WTP requirements with the exception of TTOs. The total failure to meet TTO regulations and, more specifically, the extremely high concentration of BBP, an otherwise degradable compound, must be studied further.

Species with greater density, that tend to settle, are preferred for this system in order to facilitate the retention of biomass for subsequent processing. More research and analysis would also be required to determine the movement of metals within the biomass and water phase.

Finally, significantly more research would be required to demonstrate that any degradation at all is actually occurring as opposed to a dilution and settling process. Proper shearing and emulsification of the paint is so critical to successful degradation. Without it, the paint is unavailable to the microbes for digestion. No study to date has proven substantial quantitative aerobic digestion of paint, with the exception of the VOCs contained in paint.

7.3.1.4 Post Digestion-Solid Phase

When biologically degrading paint, sludge is always left behind for various reasons. First, paint consists of many inorganic compounds and constituents that do not biologically degrade, such as metals. Secondly, it is unrealistic to believe 100% degradation of all organic material will occur. The classification of this sludge is very important to the overall economic feasibility of this process. Hazardous waste disposal is almost three times as expensive as nonhazardous waste. However, in order for the sludge to be classified as nonhazardous, it must pass TCLP for organics and metals.

Three composite samples were taken from the sludge that settled to the bottom of the reactor only after all five test runs were completed. The sampling of the sludge only occurred at the end of the project because there was no easy way to collect the sludge from the reactor. TCLP testing was conducted and the results were in compliance with all TCLP requirements.

Total metals, total organic carbon, and total solids results are listed in Tables 7 and 8. Although the sludge passed TCLP for metals, the total metals results show a significant amount of metals in the sludge. It is theorized that the metals are tied up in the sludge in a matrix that stabilizes them and keeps them from leaching. Furthermore, with proper paint analyses these types of results could be utilized in a mass balance of metals and organics to determine metal phasing and organic degradation. As indicated in Table 8, there is significant carbon remaining, indicating incomplete degradation.

Table 7. Total metals results from three sludge samples.

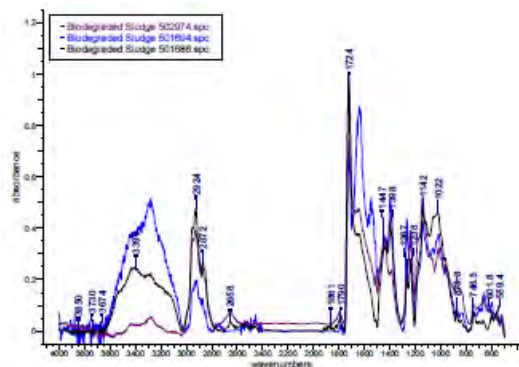
| Analyte | Sample 1 Results (mg/kg) | Sample 2 Results (mg/kg) | Sample 3 Results (mg/kg) |
|-----------|-----------------------------|-----------------------------|-----------------------------|
| Arsenic | 0.76 | 0.73 | 0.59 |
| Barium | 672 | 731 | 748 |
| Beryllium | 0.216 | 0.221 | 0.1885 |
| Cadmium | 7.19 | 6.78 | 5.7 |
| Chromium | 52.6 | 42.6 | 33.7 |
| Copper | 546 | 237 | 238 |
| Lead | 18.9 | 25.9 | 24.3 |
| Manganese | 27.1 | 38 | 32.6 |
| Mercury | 0.002 | 0.004 | ND |
| Nickel | 20.7 | 15.8 | 14.65 |
| Selenium | 0.3 | 0.2 | ND |
| Silver | 0.049 | 0.059 | 0.045 |
| Tin | 17 | 20 | 19 |
| Titanium | 384 | 510 | 507.5 |
| Zinc | 567 | 496 | 428 |
| Totals | 2,313.8 | 2,124.3 | 2,052.3 |

ND = Non-detect

Table 8. Results for total solids and total organic carbon from three sludge samples.
(% by weight)

| Analyte | Sample 1 Results (%) | Sample 2 Results (%) | Sample 3 Results (%) |
|----------------------|-------------------------|-------------------------|-------------------------|
| Total solids | 44.85 | 35.1 | 36.2 |
| Total organic carbon | 39.30 | 40.5 | 41.7 |

FTIR analysis was also utilized to characterize the sludge prior to disposal. Spectra for the three different samples taken from the bottom of the process tank are shown in Figure 12. The strong hydrocarbon peaks between the 3000 to 2800 cm^{-1} region indicate significant remaining organic matter. And, specifically, sample number 501686's peaks were compared against the commercial FTIR library, where a possible match with a mixture of resin components found in coatings was identified. Results indicate that although the spectra show partial biodegradation, the infrared behavior of the remaining sludge exhibits undigested organic resins or activator components.

**Figure 12. FTIR spectra of biodegraded resin byproduct in sludge taken from bottom of process tank.**

In summary, comparing the FTIR analysis of the sludge samples to the liquid samples (where far more biodegradation was shown), the results suggest that much of the paint, if not all, is not being degraded and is actually settling to the bottom, with the exception of the VOCs.

7.3.1.5 Post Digestion-Air Phase

Degradation of an exhaust gas with high VOC content is required to meet clean air regulations. For this system, an air-biofiltration system with an activated carbon filter at the end for polishing was installed. The success criteria for the air biofiltration system is based on Title V requirements (i.e., a reduction of 95% of VOCs entering and exiting the system). For the demonstration, the process was not required to meet these regulations. However, activated carbon for polishing was a requirement. See Table 6-24 in the Final Report for the reduction across the biofilters and exhaust system.

The biofilters were unable to ever meet the standard and, sometimes, percent reductions were below 50%, resulting in the majority of the VOC being removed by the activated carbon. However, the system did significantly improve over time. With more acclimation and more consistent run time, the unit would establish a more robust microbiological population, leading to higher removal rates.

Further consistent testing, in which the biofilters are run regularly, would likely improve operation and efficiency of the biofiltration system. With the DEM/VAL project, runs were far apart, which likely led to some population die-off. There is no way to remedy this without using simple consistent system run-times. If this was the case, and the biofilters were able to achieve a consistent 90% or greater removal of VOCs, the burden on the GAC would be less. However, the biofilters would always require an activated carbon filter to ensure Title V compliance. The air waste stream from this process is so heavily laden with VOCs, that the use of activated carbon for polishing is the third highest cost, per gallon, when running the system.

7.3.2 Qualitative Performance Objectives

The qualitative performance objectives of the DEM/VAL study focus on making the equipment more readily available for parts and assembly and the process more efficient to run. After the initial installation and subsequent delays due to inadequate design, assembly and operation of the system were successful. Though the process itself requires further investigation and study before validation is possible, the parts and equipment chosen for the system proved to be adequate and low-maintenance. Objectives from Table 1 are described and explained in detail in the following paragraphs.

The objective for procuring system parts was to use readily available, off-the-shelf components. This objective was met, even for parts procured during the initial redesign and installation.

The system assembly objective was specifically to procure and install the reactors, pumps, valves, can-crusher, and biofilters within 3 months of the contract award. Procurement and installation began within the 3-month timeline. However, system inadequacies and poor design delayed the completion of this objective for another 9 months. Additional travel and contract

modifications were required to address two major issues: biofilter design and exhaust piping incompatibility.

For the startup and optimization objective, startup did occur within 1 month of installation. Four thousand two hundred and seventy-five gal of water, 25 gal of paint, and the appropriate amount of nutrients were added to the process as an initial run, as well as for growing and acclimating microbiological population. However, an optimal environment was never reached. As the data was analyzed throughout the project, the inability to adequately shear and emulsify the paint for degradation became apparent. This is an incredibly critical point in the system. Redesign of the reactor pumps would likely be required to address the issue.

The remaining objectives (ease of operation, operator safety, operational requirements, maintenance requirements, and reliability) were all met by reducing manpower, automating, and carrying out correct operational procedures while the system was running.

7.3.3 Conclusions

NAVFAC ESC's system experience and data collation raised three major issues related to aerobically digesting ESL paint under the current design. First and foremost is cost effectiveness. The highest cost, by far, is labor. Current design and the extremely low concentration of the liquor (less than 1.5% paint) do not allow for an economy of scale for the system (i.e., not enough paint was digested to make the system economically viable because of the labor).

Electricity costs do not change whether the system can process 60 gal of paint or 600 gal of paint per treatment cycle. Therefore, the throughput of paint is too low to keep the costs of electricity more economically feasible.

GAC usage is dependent on loading and can be significantly reduced by improving degradation of the organic material. If TTO can be met by degradation alone, this would eliminate the cost of GAC for polishing the water phase prior to discharge. This can apply also to the biofilters because the more efficiently they work, the less GAC that will be needed to polish the air stream. Based upon this study, a minimum of 90% efficiency would be required to make this part of the system cost effective.

Other overall issues of treatment were the inability to adequately emulsify the paint to provide surface area for biological digestion and the lack of degradation. Redesign of the shearing process would be required to enhance biological degradation. Operating with less than optimal paint is not an option, as discussed earlier. Throughput is already too low on a cost basis and too diluted a waste stream will not provide adequate food for the microbial population. The final major issue, achieving and measuring actual degradation, will require more research for the water and solids phase.

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8.0 COST ASSESSMENT

8.1 COST MODEL

Currently, ESL paint is disposed of off-site using DRMO at a cost of \$1.10 per pound for bulk rate, equating to approximately \$9.19 per gal. Pearl Harbor activity disposal charges are \$18.90 per gal for hazardous waste and \$15.85 per gal for nonhazardous waste. The additional cost is to maintain permitting and to help pay material handling and storage costs. Cost comparison is based on DRMO disposal costs because these are the costs the system will be competing against. This paint is eventually shipped off island and incinerated in the continental United States. There are liabilities associated with shipping hazardous waste off island; therefore, onsite treatment is preferred. Biological treatment of solvent-based paint is a new approach that has not been fully proven to date. Therefore, the cost of biologically treating ESL paint onsite will be compared to off-site disposal using DRMO.

Organizations that assisted in gathering costs for this effort are NAVFAC Engineering Service Center, Naval Base Pearl Harbor, Wastewater Resources Incorporated (WRI), Santa Barbara Applied Research, Inc. (SBAR), and Biorem, Inc. NAVFAC ESC provided developmental and regulatory costs, Naval Base Pearl Harbor provided handling and disposal costs, and WRI provided costs for equipment and installation. SBAR provided estimates on reactor tanks and shipping, and Biorem, Inc., was in charge of the biofiltration system costing.

Installation costs include planning, development, drawing preparation, capital costs, shipping, installation, and regulatory negotiations. Capital costs include acquisition of equipment and ancillary and supply costs. Site preparation costs include utilities and any modifications made to existing infrastructure. Operations and maintenance (O&M) costs include manpower (operation and supervision), replacement parts, consumables (e.g., nutrients), equipment calibration, sampling, energy requirements, analytical work, and any waste handling and disposal. Although the routine operation of the system will not require significant labor, operation during the demonstration required additional labor associated with sampling, analysis, and reporting. The analytical costs associated with the sampling during the demonstration project were tracked and used to estimate analytical costs associated with future routine operation.

8.2 COST ANALYSIS AND COMPARISON

Table 9 lists the development and capital costs for the installation of the system. The table breaks down specifically the development costs, site-preparation costs, equipment costs, and installation costs. Table 7-2 lists the costs specific to the DEM/VAL.

Table 9. Total system costs.

| Category | Subcategories | Sub-subcategories | Cost |
|-------------|-------------------------|-------------------|--------------|
| Development | Site selection | | \$1,000.00 |
| | Site drawings | | \$25,000.00 |
| | System drawings | | \$100,000.00 |
| | Regulatory negotiations | | \$100,000.00 |

Table 9. Total system costs (continued).

| Category | Subcategories | Sub-subcategories | Cost |
|-------------------|----------------------|------------------------------------|--------------|
| Site Preparation | Pad | | \$25,000.00 |
| | Utilities | | \$15,000.00 |
| Capital costs | Equipment | Reactor (cone bottom) 5000 gal | \$30,000.00 |
| | | Mixing tank plus stand | \$14,000.00 |
| | | Can crusher | \$28,000.00 |
| | | Humidifier water tank | \$8,000.00 |
| | | Humidifier water transfer tank | \$10,000.00 |
| | | Mixers | \$7,500.00 |
| | | Homogenizing pumps (2) | \$20,000.00 |
| | | Biofilter system | \$60,000.00 |
| | | Activated carbon water | \$23,000.00 |
| | | Activated carbon air | \$15,000.00 |
| | | Blower | \$4,500.00 |
| | | Reactor transfer tank | \$6,500.00 |
| | | Acid and base addition system | \$4,000.00 |
| | | Nutrient addition system | \$1,700.00 |
| | | Control panel | \$16,500.00 |
| | | Piping | \$25,000.00 |
| | | Air tubing | \$250.00 |
| | | Electrical (wiring, conduit, etc.) | \$10,000.00 |
| | | Filter press | \$20,000.00 |
| | | Auger | \$2,500.00 |
| | | Cyclone separator | \$1,500.00 |
| | | Valves (manual) | \$2,500.00 |
| | | Valves (8 air actuated) | \$12,000.00 |
| | | Air compressor | \$2,500.00 |
| | | Air monitoring equipment | \$7500.00 |
| | Total Equipment Cost | | \$332,450.00 |
| | Shipping | | \$15,000.00 |
| | Installation | | \$25,000.00 |
| | Manual preparation | | \$20,000.00 |
| Total System Cost | | | \$658,450.00 |

Table 10. Extra DEM/VAL costs.

| Category | Subcategories | Sub-subcategories | Cost |
|--------------------------------|------------------|-----------------------|--------------|
| DEM/VAL costs only | Labor | Sampling | \$303.00 |
| | | Pearl Harbor analysis | \$500.00 |
| | | Reporting | \$27,000.00 |
| | Analytical costs | | \$82,000.00 |
| Total DEM/VAL Additional Costs | | | \$109,803.00 |

Table 11 lists the costs for the few parts that will require replacement throughout the system's life cycle. Table 12 shows the O&M costs based on the DEM/VAL VOC results in the biofiltration system, and Table 13 shows the O&M costs based on a biofiltration system that is running at 90% efficiency.

Table 11. Equipment replacement costs for life of the paint treatment system.

| Part | Cost | Life-Cycle (yrs) | No. Replacements Based on a 15-Year Facility | Life-Cycle Cost |
|----------------|-------------|-------------------------|---|------------------------|
| Blower | \$4,500.00 | 10 | 1 | \$4,500.00 |
| Air compressor | \$2,500.00 | 10 | 1 | \$2,500.00 |
| Pump | \$12,000.00 | 10 | 1 | \$12,000.00 |
| Pump | \$8,000.00 | 10 | 1 | \$8,000.00 |
| Probes | \$2,000.00 | 1 | 15 | \$30,000.00 |
| Total | | | | \$57,000.00 |

Table 12. Operational costs based on DEM/VAL conditions.

| Type | Condition | Amount | Unit Cost | Time (hrs) | Total Cost / 24 hrs | Total Cost for 4 day run | Cost / Gal Paint |
|---|--|-----------------------|------------------|-------------------|----------------------------|---------------------------------|-------------------------|
| Electricity | System's total horse power (HP) = 23.25 | 17.34 kw | \$0.17/kwh | 24 | \$71.19 | \$284.75 | \$4.75 |
| Water | Volume required per run per train | 2,000 gal per run | \$2.02/K-gal | N/A | N/A | N/A | \$0.07 |
| Acid | For pH control | 2 gals | \$3.00/gal | N/A | N/A | \$6.00 | \$0.10 |
| GAC-air | GAC required for polishing air based on DEM/VAL data | 7.0 lb per day | \$5.50/lb | N/A | \$38.85 | \$155.39 | \$2.59 |
| GAC-water | GAC required for polishing water per DEM/VAL data | 0.005267 lb/gal water | \$5.50/lb | N/A | N/A | \$57.95 | \$0.97 |
| Nutrients | N-Z amine | 8.25 lb/run | \$10.55/lb | N/A | N/A | \$87.04 | \$1.45 |
| | Yeast extract | 8.25 lb/run | \$4.45/lb | N/A | N/A | \$36.71 | \$0.61 |
| | Urea | 23.05 lb/run | \$0.41/lb | N/A | N/A | \$9.43 | \$0.16 |
| | Phosphate | 11.15 lb/run | \$0.26/lb | N/A | N/A | \$2.91 | \$0.05 |
| Disposal | Nonhazardous sludge | 698.00 lb | \$0.45/lb | N/A | N/A | \$314.10 | \$1.42 |
| Labor | Manpower | 5 hr | \$75.00 | N/A | N/A | \$375.00 | \$6.25 |
| Life-cycle costs | Equipment replacement | N/A | N/A | N/A | N/A | N/A | \$1.22 |
| Total operational cost / gal paint | | | | | | | \$19.64 |

Table 13. Operational costs based on ideal biofilter performance.

| Type | Condition | Amount | Units | Unit Cost | Units | Time (hrs) | Total Cost / 24 hrs | Total Cost for a 4 Day Run | Cost / Gal Paint |
|---|---|---------|--------------|-----------|-------|------------|---------------------|----------------------------|------------------|
| Electricity | System's total HP = 23.25 | 17.34 | kw | \$0.17 | kwh | 24 | \$71.19 | \$284.75 | \$4.75 |
| Water | Volume of water required per run per train | 2000 | gal/run | \$2.02 | K-gal | N/A | N/A | N/A | \$0.07 |
| Acid | For pH control | 2 | gal | \$3.00 | gal | N/A | N/A | \$6.00 | \$0.10 |
| GAC-Air | GAC required for polishing air based on 90% removal efficiency for biofilters | 1.65 | lb/d | \$5.50 | lb | N/A | \$9.05 | \$36.21 | \$0.60 |
| GAC-Water | GAC required for polishing water based on DEM/VAL data | 0.00527 | lb/gal-water | \$5.50 | lb | N/A | N/A | \$57.95 | \$0.97 |
| Nutrients | N-Z Amine | 8.25 | lbs/run | \$10.55 | lb | N/A | N/A | \$87.04 | \$1.45 |
| | Yeast Extract | 8.25 | lbs/run | \$4.45 | lb | N/A | N/A | \$36.71 | \$0.61 |
| | Urea | 23.05 | lbs/run | \$0.41 | lb | N/A | N/A | \$9.43 | \$0.16 |
| | Phosphate | 11.15 | lbs/run | \$0.26 | lb | N/A | N/A | \$2.91 | \$0.05 |
| Disposal | Non-hazardous sludge | 698.00 | lbs | \$0.45 | lb | N/A | N/A | \$314.10 | \$1.42 |
| Labor | Requires 5 man hours | 5 | hrs | \$75.00 | \$\$ | N/A | N/A | \$375.00 | \$6.25 |
| Life Cycle Costs | Equipment replacement | N/A | N/A | N/A | N/A | N/A | N/A | N/A | \$1.22 |
| Total operational cost/gal paint | | | | | | | | | \$17.65 |

No facility capital costs are calculated because the project did not propose to build a facility or building. System capital costs and life-cycle costs are based on the assumption that the system would be installed in a preexisting structure within an operating waste treatment facility.

All O&M costs (Tables 12 and 13), except for disposal, are based on a 4-day, 60-gal treatment run. Labor for operation, supervision, sample collection, and waste handling was estimated to average about five man hours per run. Disposal volume is based on DEM/VAL results. All test run results used for analyzing were completed in system B. Two hundred twenty-three gal of treated paint yielded approximately 220 gal of wet sludge. Analysis of the wet sludge showed it was approximately 38% solids. Because the wet sludge was never weighed and the specific gravity of the paints were all approximately 1, it was decided to use this figure for the wet sludge. Based on this assumption, this would yield 698 lb of sludge for disposal after dewatering. It could be argued that the specific gravity of the sludge is higher than 1, increasing the pounds of sludge requiring disposal. However, for this demonstration it will have little bearing. In addition, though this system was not outfitted with an auger, which would dramatically reduce the cost of sludge handling, the costs were calculated based on a reactor with appropriate desludging capability.

As discussed in Section 6.0 of the Final Report, the operation of this system is the single largest contributing factor to the excessive life-cycle cost. The issue stems from two major sources as indicated in Tables 12 and 13: electricity and labor. As indicated in Tables 6-3 and 6-4 of the Final Report, the cost of disposing of hazardous waste by DRMO (in this case, paint) is \$9.19 per gal. In order for the system to be cost effective, the operational and maintenance costs would have to be less than this figure. However, as it stands, it's at \$19.63 and \$17.61 for DEM/VAL conditions and for operations when the biofilter efficiency is at 90%, respectively. Labor and electricity alone exceeds the \$9.19 threshold. While electricity might be less expensive elsewhere, the cost to provide energy to the system is still too expensive with current fuel and energy costs.

In summary, without improving throughput of paint, the process can never be cost effective. As stated before, factors contributing to the elevated costs, in order of significance, are throughput (affects fixed costs [i.e., labor, electricity]), kwh cost, activated carbon, N-Z amine, and degradation efficiency of the paint. In order to have a chance of making this process cost effective, the current system throughput would have to be increased from 60 gal to a minimum of 200 gal per treatment cycle. This would dramatically reduce the fixed costs, such as labor and electricity. After this has been accomplished, degradation needs to be maximized to the extent possible in both phases (i.e., air and water) to reduce costs associated with activated carbon use and reduce total sludge disposal costs. Recycling the water after treatment to the extent possible will also reduce the amount of carbon required. Finally, the requirement for N-Z amine needs to be looked at very closely. At current dosing, this nutrient alone contributes \$1.45 per gal of paint, which is significant. There are great challenges ahead that have to be overcome before biological treatment of solvent-based paint can become economically viable.

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9.0 IMPLEMENTATION ISSUES

The scale-up from pilot to DEM/VAL proved to be premature. Results and information were inconclusive and lacking in the pilot report, and after the DEM/VAL, much is still unknown about the process. The majority of the work and research during the DEM/VAL should have been completed on the pilot scale. Moving a treatment system to this scale requires a much better understanding of the process. Because of this, major operational issues were encountered and discussed in previous sections of this report. If the process were to become economically viable, there would be two major implementation issues to contend with—permitting and system operators.

First, a Part B permit would be required. For installations that already possess a Part B permit, modification to their existing permit would be required. How long this would take and the exact costs associated with this process are unknown. Because biological treatment of solvent-based paint has never been done before, it is possible that additional requirements that do not currently exist may be imposed upon the process due to the complex organic chemistries associated with this waste. For facilities that are not operating under a Part B permit, a new permit would be required, and this would definitely require additional time.

Secondly, personnel staffing requirements would need to be established. This system is a delicate process, requiring a highly skilled level of operators to ensure its success. Substantial training would be required and individuals in charge of the system would have to be proven, highly motivated individuals. Although the system is self-sufficient when running properly, an upset in the process can quickly become a crisis, and personnel must be able to have the knowledge to act quickly and correctly.

9.1 LESSONS LEARNED

Because of operational issues that became evident during the various runs, revisions to the SBR system have been proposed. The revised SBR proposal is shown in Figure 13. Each of the revisions will be discussed below.

One of the most critical issues encountered during the demonstration was the insufficient emulsification of the paint in the mixing tank. It became clear that the pumps supplied with the system were incapable of shearing the paint and, therefore, degradation of the paint was adversely affected. Pumps designed to shear liquids with relatively high viscosity would be required. These pumps would be used to shear the paint in the mixing tank as well as in the reactor, as shown in Figure 13.

The reaction tanks also had some deficiencies associated with them. Based on the solids found in the reactor, settleable solids will be formed regardless of the efficiency of the degradation process. The metals found in the paints will not be degraded and, therefore, will eventually settle to the bottom of the reactors. Unfortunately, as designed, there is not a simple way of removing the solids accumulating at the bottom of the reactors without having to empty the reactors first. Then someone has to enter the reactor to remove the solids. From an operational perspective, this situation is unacceptable. The reactors should have been configured with a cone bottom retrofitted with an auger. This type of setup would allow an operator to remove solids that settle

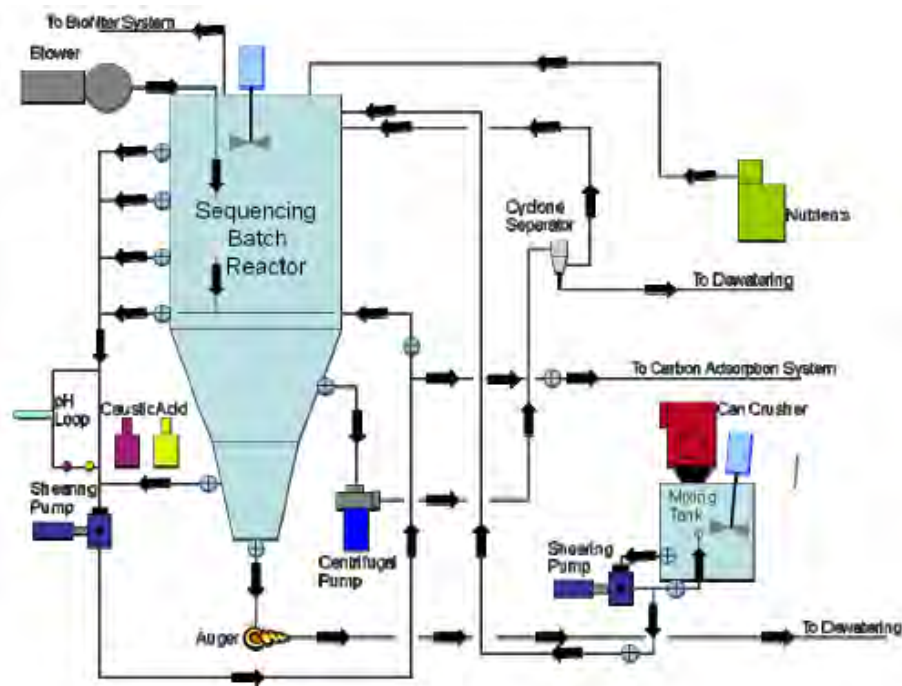


Figure 13. Revised SBR biological treatment system for ESL solvent-based paint system.

to the bottom of the reactor without having to empty the vessel or having to climb inside the vessel. In addition, one could remove the solids during operation, if desired. This would dramatically reduce the labor required to run such a system.

A cyclone separator would be a nice addition to the system. We found the bacteria hard to concentrate and never really reached a high enough concentration in the reactor to be considered satisfactory. The cyclone separator could be used to remove bacteria from the reactor when required or to concentrate the bacteria without having to wait for the bacteria to settle, which can take up to 24 hours or more.

Finally, not shown in the figure, is an additional tank. Having an additional tank would allow the system to recycle the water several times before having to dispose of it. This would reduce dramatically the use of activated carbon to remove residual organics left in the water phase. It also would reduce the amount of nutrients used because the unused nutrients would be recycled back to the reactor for another treatment cycle.

All the items mentioned above would reduce dramatically the labor costs and increase the efficiency of the system. It is anticipated that labor costs alone could be reduced by a factor of three to four if these items were incorporated. In addition, Hawaii has one of the most expensive electricity costs within the United States. If the demonstration had been conducted within the contiguous United States, this cost could have been reduced by at least 50%.

With this being said, plans are in place to improve the current system to the extent possible. NAVFAC ESC received funding from Naval Base Hawaii to implement some of the items

mentioned above. In addition, further testing will be conducted in order to improve degradation of the paints in order to reduce sludge generated from the system. After these modifications have been incorporated and testing completed, the system will be put online. Naval Base Hawaii envisions someday treating all of Hawaii's DoD unused paints.

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APPENDIX A POINTS OF CONTACT

| Point of Contact | Organization | Phone Fax E-Mail | Role In Project |
|-------------------------|--|---|--------------------------|
| Tom Torres | NAVFAC ESC 1100 23rd Avenue Port Hueneme, CA 93043 | Phone: (805) 982-1658 E-mail: Tom.torres@navy.mil | Project Engineer |
| Jenny Lagerquist | SBAR, Inc. 2151 Alessandro Drive Suite 220 Ventura, CA 93001 | Phone: (808) 888-0073 E-mail: jlagerquist@hawaii.rr.com | Contract Support |
| Steve Christiansen | Naval Base Pearl Harbor 400 Marshall Road Building 223 Pearl Harbor, HI 96860 | Phone: (808) 474-0392 E-mail: Steven.christiansen@navy.mil | Host Site Coordinator |

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APPENDIX B

SCHEMATIC OF BIOLOGICAL TREATMENT SYSTEM

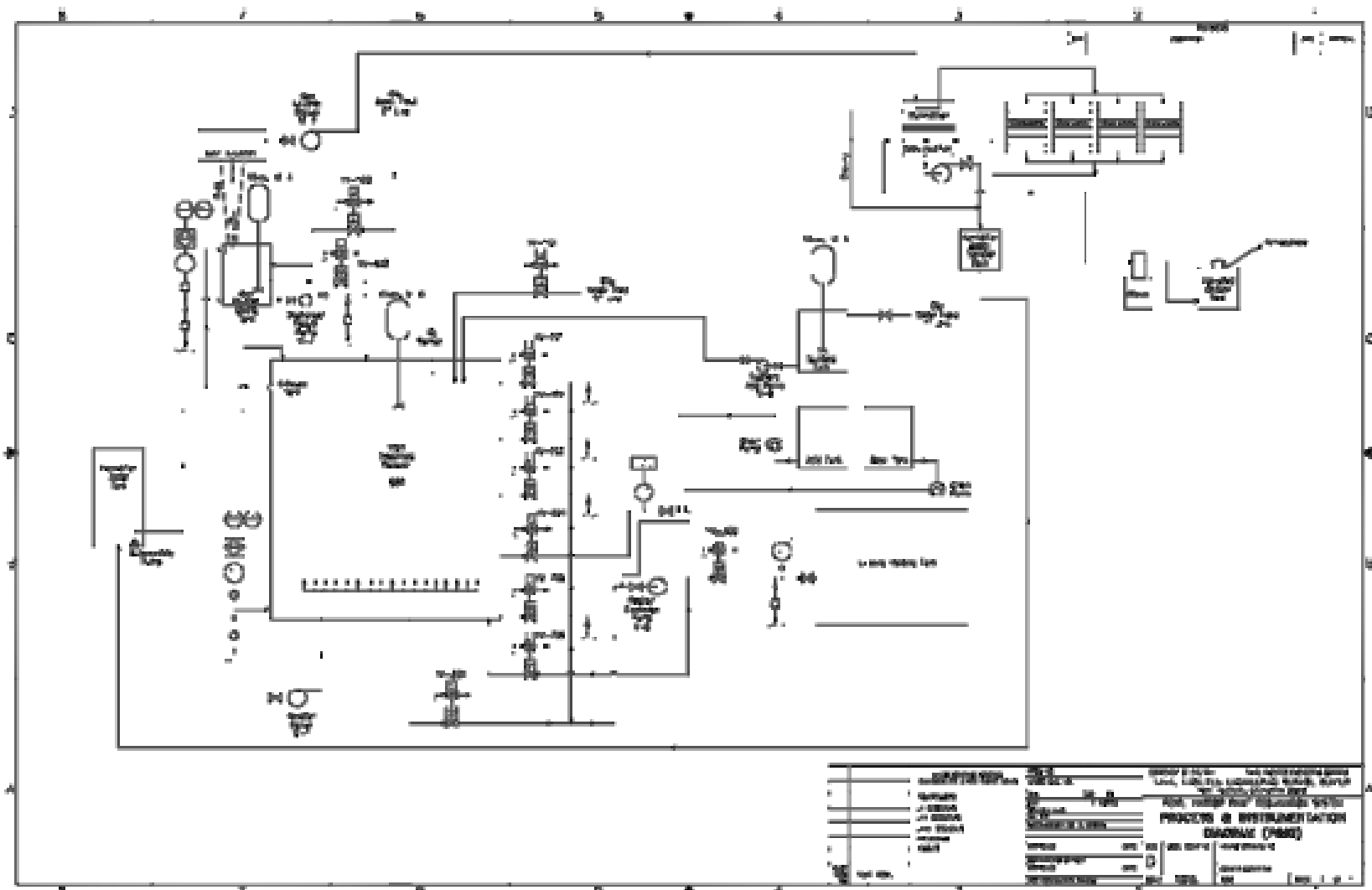


Figure B-1. Schematic drawing of the biological treatment system for expired shelf life paint.



ESTCP Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

E-mail: estcp@estcp.org
www.serdp-estcp.org